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1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
6 June 1994

3. REPORT TYPE AND DATES COVERED
Final 3/1/91-2/28/94

4. TITLE AND SUBTITLE
Scanning Tunneling Microscopy of III-V Semiconductors

5. FUNDING NUMBERS
DAAL03-91-G-0054

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8. PERFORMING ORGANIZATION REPORT NUMBER
JDD-694F

DTIC ELECTE JUL 18 1994 S G D

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
ARO 28508.7-EL

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
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12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
Scanning tunneling microscopy and theory were comined to (1) create novel depressive quantum dots at room temperature on the (110) surfaces of InSb --- dots which merit further exploration as potential nanopixels for tiny-device lithography; (2) develop a strained-layer superlattice model of high-temperature superconductivity; (3) image, understand, and make models of single-atom-high steps on III-V surfaces; (4) invent and exploit a new kind of spectroscopy of surface states of semiconductors, called "tipology;" (5) develop phenomenological models of a variety of surface phenomena.

94-21353

DTIC QUALITY INSPECTED 5

94 7 12 248

14. SUBJECT TERMS
Scanning tunneling microscopy

15. NUMBER OF PAGES
6

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

SCANNING TUNNELING MICROSCOPY OF III-V SEMICONDUCTORS

FINAL REPORT

John D. Dow

6 June 1994

U. S. ARMY RESEARCH OFFICE

CONTRACT NUMBER DAAL03-91-G-0054

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I. Report

A. Statement of problem studied

Beginning with a mission to study the surfaces of III-V semiconductors with scanning tunneling microscopy and with theory, we learned how to use the scanning tunneling microscope (STM) to make artificial structures on the surfaces of III-V semiconductors, established the basic science of single-atom-high steps on III-V surfaces, invented a new kind of spectroscopy called "tipology" for investigating difficult to image states of semiconductor surfaces, observed, explained, and understood a variety of data for semiconductor surfaces, and then applied the ideas we had developed for strained-layer superlattices to provide a solution to one of the "hottest" science problems of the day: the physics of high-temperature superconductivity.

B. Summary of the most important results

During the course of this project, we have accomplished the following:

1. Quantum dots

We have fabricated quantum dots on the (110) surface of InSb, using a scanning tunneling microscope as a fabrication tool [266]. Specifically the field under the microscope tip is able to drill a hole one or two atoms deep without the tip touching the surface. Some degree of spatial location of the dots was achieved. These results demonstrate that it is feasible to make patterns at room temperature on an atomic scale on this surface — and raise the possibility of patterning devices on the atomic scale, a goal that could be achieved if (i) more control on returning to the location of a dot is achieved, and (ii) schemes for converting the patterns into electronic structures are developed (by filling each dot with a particular material, such as a superconductor, for example).

2. High-T_c superconductivity

In the course of studying strained-layer superlattice materials composed of III-V semiconductors, we realized that many of the high-temperature superconductors have strained-layer superlattice properties. This led us to investigate the problem of superconductivity in the high-temperature oxide superconductors, and we developed a theory which is in marked disagreement with the many current theories (none of which is regarded as "correct"), determined that it explained hundreds of experiments, and isolated the tenet of most contemporary theories that is responsible for mis-directing the field. This tenet is the assumption that the superconductivity originates in the cuprate planes. In fact, there are high-temperature superconductors that have no cuprate planes, no copper, and no layered structures, such as $Ba_{1-a}K_aPb_{1-b}Bi_bO_x$, which proves that cuprate planes are not essential to high-temperature superconductivity, and therefore disproves virtually all of the current theories.

Our viewpoint [295,308,310,320-322,326] is that dopant oxygen, which is substitutional in $YBa_2Cu_3O_{7-\delta}$, and interstitial in many other superconductors (*e.g.*, $La_{2-\beta}Sr_\beta CuO_{4-\delta}$) is the root of superconductivity in the high-T_c oxides in general: holes associated with this dopant oxygen pair through the polarization field of the material and form a BCS-like superconductor. There is a great deal of evidence to support this viewpoint. Perhaps the best is available from pair-breaking data, which are all explained by our confined-oxygen model, and unexplained by the cuprate-plane models: Pair-breaking by exchange scattering is short-ranged, and so affects almost exclusively atoms that are nearest-neighbors to the magnetic impurity (usually a rare-earth) that is responsible for the observations. Thus we can think of magnetic pair-breaking as a short-ranged and local experimental probe. We have successfully explained all of the pair-breaking data that we have been able to find, including dependences on site, host crystal-structure, the magnetic ions, crystal-field splittings, orbital and total angular momentum quantum numbers L and J, and ionic size. These many complicated dependences come from only two notions: (i) the superconductivity is rooted in the dopant oxygen (*e.g.*, chains, not planes, in $YBa_2Cu_3O_{7-\delta}$ systems; interstitials in some materials); and (ii) magnetic impurities more distant than nearest neighbors from this oxygen do not break pairs.

These ideas led to the prediction that $PrBa_2Cu_3O_7$ should exhibit granular superconductivity, for grains that do not contain any Ba-site Pr, and this prediction has been verified [326]. They also imply that it should be possible to develop integrated superconductor/semiconductor devices — but it will take some time to achieve this goal [310]. At the very minimum, our ideas should completely alter the main tenet of most contemporary theories of high-temperature superconductivity: that the superconductivity originates in the cuprate planes. They are likely to have considerably more impact, however, and our confined metallic oxygen model may eventually be adopted as providing the solution to the main theoretical problem: What causes superconductivity in these materials?

3. Steps and dimerization on step edges

We have done pioneering work on the physics of single-atom-high steps on the surfaces of InAs, InSb, and InP (110) surfaces. We have observed such single-atom-high steps for the first time, and shown that the step edges dimerize. We have developed several models of different steps, and shown that they are compatible with the measurements. As such, we have laid the foundation for studying and understanding nucleation, growth, and contact formation on these surfaces.

4. Tipology

We have developed the notion that scanning tunneling microscopy/spectroscopy (STM/STS) can use an "active" tip [306]. By this we mean that the microscope itself can be constructed to give it special properties. In our case, we have used a SiC STM tip (instead of the usual W tip) to image the (111)-7×7 surface of Si, using the forbidden band gap of SiC to filter out certain tunneling transitions at certain energies. This work, performed in collaboration with Nobel Laureate Heinrich Rohrer, demonstrates that active tips lead to new physics, provide new insights into the Schottky barrier problem, and may lead to entire new classes of experiments.

5. Phenomenology

We have executed a number of calculations in order to support various experiments [275,277,281,294] and to clarify observations and identifications of nanoscopic structures.

Perhaps the most important of these calculations showed that the β-SiC(111) surface is covered with a layer of (nearly) graphite, which masks STM tunneling, so that only the dangling bonds below holes in the mask can tunnel out of the surface. This clarified and established the graphitic-monolayer model of this surface. We have also established that subsurface layers of InSb(110) can be imaged with STM, but that the image is ethereal, disappearing as the bias voltage is altered. This work establishes the utility of combined theoretical and experimental investigations of surfaces, and elevates the STM to being a probe capable of examining with high resolution some issues relevant to buried monolayers.

C. Publications

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310. H. A. Blackstead, J. D. Dow, and D. B. Pulling. Oxide superconductivity: Integrated, photo-induced high-temperature superconductivity. Submitted.

320. H. A. Blackstead and J. D. Dow. Role of Ba-site Pr in quenching superconductivity of $Y_{1-y}Pr_yBa_2Cu_3O_x$ and related materials. Submitted.

321. H. A. Blackstead and J. D. Dow. Implications of Abrikosov-Gor'kov exchange scattering for theories of high-temperature superconductivity. Submitted.

322. H. A. Blackstead, J. D. Dow. Tb doping of $YBa_2Cu_3O_{7-\delta}$. Submitted.

326. H. A. Blackstead, D. B. Chrisey, J. D. Dow, J. S. Horwitz, A. E. Klunzinger, and D. B. Pulling. Observation of superconducting $PrBa_2Cu_3O_7$. Manuscript in final stages of preparation.

D. Scientific Personnel

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Co-investigator William E. Packard
Research Scientist Min-Hsiung Tsai
Research Scientist Shang Yuan Ren
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E. Inventions: None

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